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ELECTRON-CYCLOTRON MASER EMISSION DURING FLARES: EMISSION IN VARIOUS MODES AND TEMPORAL VARIATIONS

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ABSTRACT. Absorption of radiation at the electron-cyclotron frequency, Ω_e, generated by the electron-cyclotron maser instability has been proposed as a possible mechanism for transporting energy and heating of the corona during flares. Radiation from the same instability but at harmonics of Ω_e is believed to be the source of solar microwave spike bursts. The actual mode and frequency of the dominant emission from the maser instability is shown to be dependent on (i) the plasma temperature, (ii) the form of the energetic electron distribution and (iii) on the ratio of the plasma frequency ω_p to Ω_e. As a result, the emission along a flux tube can vary, with emission at harmonics being favored in regions where $\omega_p/\Omega_e \gtrsim 1$. Changes in the plasma density and temperature in the source region associated with the flare can also cause the characteristics of the emission to change in time.

1. INTRODUCTION

Solar microwave spike bursts and very bright and highly polarized spike bursts from flare stars and close binaries have been attributed to the electron-cyclotron maser instability (Holman et al., 1980; Melrose and Dulk, 1982a; Sharma et al., 1982; Gary et al., 1982; Dulk et al., 1983). Partial absorption of the radiation as it propagates through the corona is also thought to produce heating of coronae during solar and stellar flares (Melrose and Dulk, 1982b, 1984; Winglee, 1985a,b).

The maser instability arises as follows. Electrons are accelerated at some point along a flux tube tied to the star. As they propagate toward the footpoint of the flux tube (i.e., towards increasing magnetic field) their perpendicular velocity increases at the expense of their parallel velocity due to the conservation of the adiabatic invariant. With the precipitation of low pitch angle electrons, two types of distributions can develop: a loss-cone distribution if the electrons are injected continuously into the flux tube, or a distribution which is peaked at high pitch angles if the electrons are injected impulsively (White et al., 1983). Both types of distributions have a positive $\partial f/\partial v_\perp$ which can drive the maser instability. Maser emission at the fundamental is likely to be reabsorbed in the corona and produce heating; higher harmonic radiation can escape to produce the observed radio burst.

The mode and frequency of the dominant emission from the maser instability are dependent on the plasma temperature, the form of the energetic electron distribution and on the ratio of the plasma frequency ω_p to the electron-cyclotron frequency Ω_e (Winglee, 1985a,b). In this paper we review the characteristics of the maser emission and discuss the implications for maser emission during flares.

2. KINEMATIC CONDITIONS

The mode and frequency of the dominant maser emission is dependent on ω_p/Ω_e due to restrictions on the frequency of a given mode imposed by the cut-offs and/or resonances of the mode (Winglee, 1985a,b). These cutoffs and/or resonances are increasing functions of ω_p so that for a fixed s and a sufficiently high ω_p, these cutoffs can exceed $s\Omega_e$ and growth at harmonic s becomes suppressed.

Specifically, the dominant maser emission assuming that the energetic particles have velocities of the order of 0.1c is

(i) fundamental x mode when $\omega_p/\Omega_e \lesssim 0.3$;

(ii) fundamental z or o mode or second harmonic x mode when $0.3 \lesssim \omega_p/\Omega_e \lesssim 1$;

(iii) fundamental z mode or second harmonic x mode when $1 \lesssim \omega_p/\Omega_e \lesssim \sqrt{2}$;

(iv) second harmonic o mode or third harmonic x mode when $\sqrt{2} \lesssim \omega_p/\Omega_e \lesssim \sqrt{3}$;

(v) second harmonic z mode when $\sqrt{3} \lesssim \omega_p/\Omega_e \lesssim \sqrt{6}$.

3. VARIATIONS WITH PLASMA TEMPERATURE

The above ranges in which growth in a given mode can dominate are only approximate and they can be significantly modified when the plasma becomes sufficiently hot. This is most pronounced for the x mode when $\omega_p^2/\Omega_e^2 \ll 1$. Under these conditions, a non-zero plasma temperature can significantly reduce the x-mode cutoff and allow x-mode growth to dominate at larger ω_p/Ω_e, up to about 0.6 (Winglee, 1985a).

This dependence of the maser emission on the plasma temperature is illustrated in Fig. 1 which shows the maximum growth rates in $\omega - \underset{\sim}{k}$ space for the o, x and z modes at the fundamental. The electrons are assumed to have a Dory, Guest and Harris (DGH) distribution of the form

$$f = \left((2\pi)^{3/2} v_T^3\ j!\right)^{-1} \left(v_\perp/\sqrt{2}\ v_T\right)^{2j} \exp\left(-v^2/2v_T^2\right)$$

which is peaked at $v_z = 0$, $v_\perp = \sqrt{2j}\ v_T$. In Fig. 1, j = 1 with (a) $v_T/c = 0.2$ and (b) $v_T/c = 0.3$. It is seen that in each case, the maximum growth rate for the x mode initially increases with ω_p/Ω_e. However, in Fig. 1a once ω_p/Ω_e increases past 0.45 the x-mode growth rate decreases rapidly and z-mode growth rate dominates. In Fig. 1b, x-mode growth does not become suppressed until $\omega_p/\Omega_e = 0.65$.

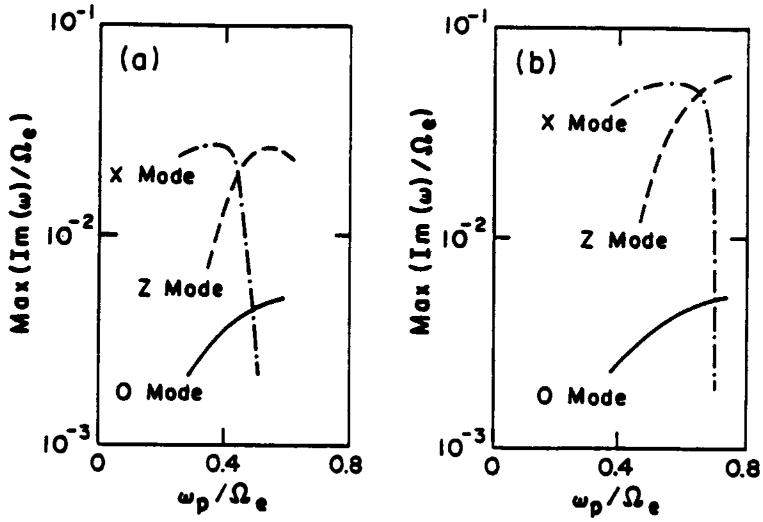

Fig. 1. Maximum growth rates for the o, x and z modes at the fundamental at a function of ω_p/Ω_e for a j= 1 DGH distribution with (a) $v_T/c = 0.2$ and (b) $v_T/c = 0.3$.

4. VARIATIONS WITH THE ELECTRON DISTRIBUTION

When ω_p/Ω_e is sufficiently high that fundamental x-mode growth is suppressed, then growth is not necessarily restricted to one mode and frequency for a given ω_p/Ω_e. Rather the dominant mode depends on the form of the electron distribution, specifically on:

(a) the relative density of the energetic electrons to any background component;

(b) the pitch angle of the energetic electrons driving the maser instability.

In particular when ω_p/Ω_e is $\lesssim 1$ and sufficiently large that fundamental x-mode growth is suppressed, fundamental z-mode growth tends to dominate if the density of the energetic electrons is much larger than that of the background component. This is illustrated in Fig. 2 which shows the maximum growth rates for $0.4 \lesssim \omega_p/\Omega_e \lesssim 2.4$ and where the energetic electrons have a j = 1 DGH distribution with $v_T/c = 0.075$. In Fig. 2a there is no cold background component while in Fig. 2b the plasma frequency of the energetic component ω_{pE} is held fixed at $0.2\ \Omega_e$ and the plasma frequency of the cold component ω_{pc} is varied. (For the illustrated range of ω_p/Ω_e, fundamental x-mode growth is suppressed.) In Fig. 2a fundamental z-mode growth dominates for $\omega_p/\Omega_e \lesssim 0.7$ while in Fig. 2b, for the same range of ω_p/Ω_e, both fundamental x-mode and z-mode growth are suppressed and fundamental o-mode dominates.

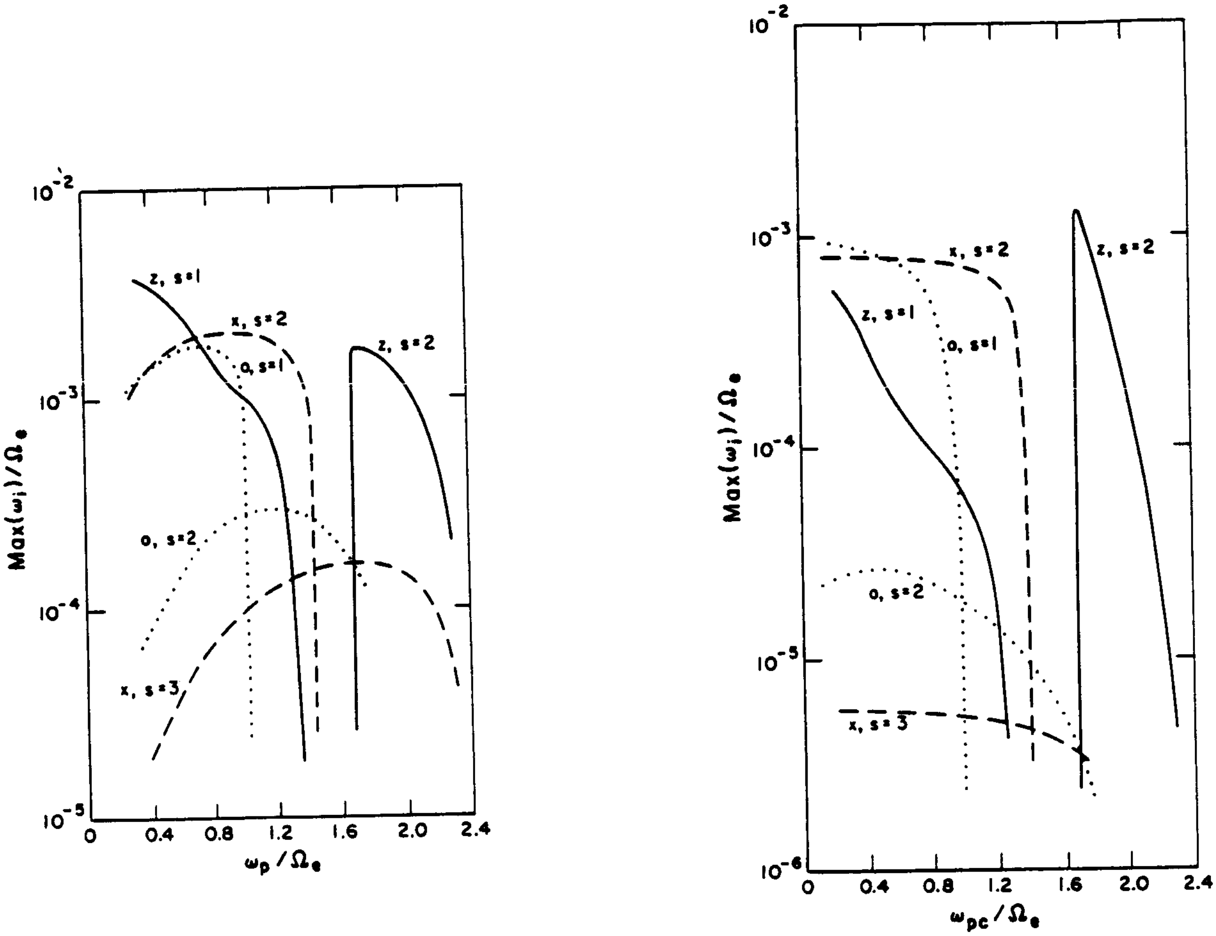

Fig. 2. Maximum growth rates for the o, x and z modes for the case where the energetic electrons have a j = 1 DGH distribution with v_T/c = 0.075. In (a) there is no background component (i.e., $\omega_{pc} = 0$, $\omega_p = \omega_{pE}$), and, in (b) ω_{pE} is held fixed at 0.2 Ω_e.

The pitch angles of the energetic electrons driving the maser instability also play an important role in determining the fastest growing mode. Specifically, when the distribution is such that $\partial f/\partial v_\perp > 0$ lies in regions of velocity where $v_\perp^2/v_z^2 \lesssim 1$ (i.e., where the electrons driving the instability have small pitch angles) o-mode growth is favored over x-mode growth; when $\partial f/\partial v_\perp > 0$ lies in regions where $v_\perp^2/v_z^2 \gg 1$, x-mode growth is favored (Winglee, 1985b). This is illustrated in Fig. 3 which shows the maximum growth rates for the same parameters as in Fig. 2b except that j = 2 rather than j = 1. The effect of the larger j is to move the peak of the distribution to higher pitch angles. In Fig. 3 there is no value of ω_p/Ω_e for which the o-mode growth rate is largest, contrary to Fig. 2b. On the other hand, when the energetic electrons have a loss-cone distribution with a small loss-cone angle, growth of the o-mode tends to be faster than that of the x mode at s > 2 (i.e., except at the fundamental for $\omega_p/\Omega_e \lesssim 0.3$ (Melrose et al., 1984)).

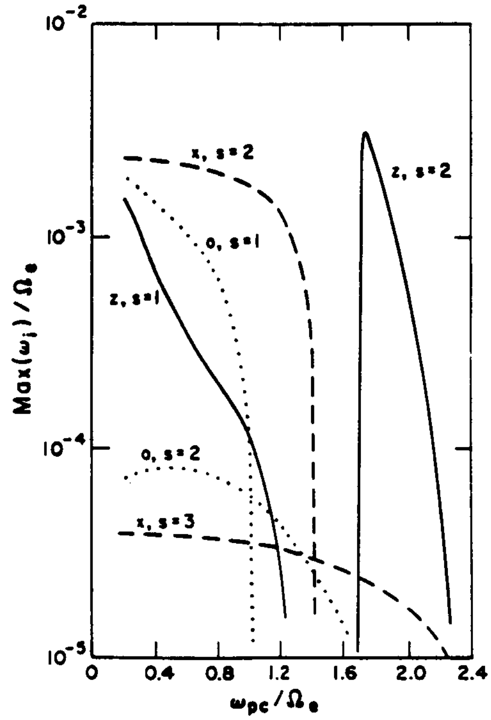

Fig. 3. As in Fig. 2b except that $j = 2$ rather than $j = 1$.

5. SUMMARY AND DISCUSSION

In this paper, the characteristics of the dominant emission from the electron-cyclotron maser instability have been examined. As ω_p/Ω_e is increased, the mode of the dominant emission changes and the frequency moves to higher harmonics of Ω_e. Fundamental x-mode growth tends to be restricted to plasmas where $\omega_p/\Omega_e \lesssim 0.3$; growth at higher ω_p/Ω_e can occur if the plasma becomes sufficiently hot. When fundamental x-mode growth is suppressed and $\omega_p/\Omega_e \lesssim 1$, the dominant emission can be fundamental o- or z-mode or second harmonic x mode, depending on the form of the energetic electron distribution. Growth of the x-mode over the o-mode is favored if $\partial f/\partial v_\perp > 0$ lies in regions where $v_\perp^2 \gg v_z^2$ (e.g., if the energetic electrons are impulsively injected into the flux tube) while o-mode growth is favored if $\partial f/\partial v > 0$ lies in regions where $v_\perp^2 \lesssim v_z^2$ (e.g., if the electrons are continuously injected into the flux tube).

During a flare, the above dependences of the emission on ω_p/Ω_e, the plasma temperature and the form of the distribution may cause the characteristics of the maser emission to change. For example, suppose that the initial conditions within the flaring flux tube favor fundamental z-mode growth. This radiation is trapped in the vicinity of the source region and is likely to be reabsorbed locally and heat the ambient electrons. If most of the electrons in the flaring flux tube become hot, the increase in temperature can cause the dominant radiation from the maser instability to switch from the z-mode to the x-mode. This x-mode radiation can escape from the source region, but, it is likely to be reabsorbed higher in the corona (the plasma overlying the source region is believed to be optically thin only for radiation at $\omega \geq 2\,\Omega_e$). This reabsorption can produce heating of the plasma away from the source region. Should the plasma in the flaring flux tube then cool (e.g., by radiation or conduction losses) the maser emission may switch back to the z-mode, and the process of switching between x- and z-modes may repeat.

Furthermore the maser emission at the beginning of a flare may be different from that at the end. The flow of cold electrons evaporated from the bottom of the flux tube and/or electrons associated with the return current for the precipitating electrons can cause ω_p/Ω_e to increase within the flaring flux tube. In this case the emisson can move to a different mode or to a higher harmonic of Ω_e. Also the distribution of the energetic electrons is most likely to have a loss-cone anisotropy at the end of the flare since this type of anisotropy tends to occur when the acceleration of the electrons lasts for any extended period. Hence, at least in the final stages of the flare, o-mode growth may be favoured, provided that $\omega_p/\Omega_e \gtrsim 0.3$ and the density of the energetic electrons is not too large.

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